Is modern Arctic Ocean circulation exceptional?

Arctic Ocean circulation as we know it today is an exceptional situation compared with the geological past. This was shown from geochemical analyses of a unique marine sediment core recovered in the central Arctic Ocean. A major transition from oxygen-poor sediments to well oxygenated sediments 17.3 million years ago indicates that the Fram Strait, which is the only deep water connection of the Arctic Ocean with the Atlantic Ocean, already opened at this time and allowed the establishment of a well-ventilated ocean basin. Isotope geochemical results suggest that the Arctic deep circulation was strongly influenced by sea ice formation during most of the past 15 million years and was not predominantly controlled by inflowing Atlantic waters, as is the case today.

The Arctic Ocean only has a limited exchange with the global ocean, whereby the Fram Strait between Greenland and Svalbard is the only deep water connection to the Atlantic Ocean. It is this connection that allows the supply of oxygen to the deep Arctic Ocean. Most previous studies based on tectonic models suggested that the opening of the Fram Strait for deep water exchange between the two basins occurred at about 10 million years ago. This could not be further investigated because, despite the fact that the Arctic Ocean has been a sensitive responder and potentially an important driver of global climate change, the Arctic's pre-Quaternary oceanographic history (prior to about 500,000 years ago), including the transition from a "greenhouse" to an "icehouse" world, has until recently been inaccessible due to a lack of continuous sedimentary records. This was mainly due to the technical difficulties to drill long sediment cores in an ice-covered ocean.

The central Arctic sediments recovered in summer 2004 during the ACEX expedition (IODP Leg 302) near the North Pole on the Lomonosov Ridge (87°5N, 137°E; 1250 m water depth) provided, for the first time, a continuous sedimentary archive, from which Neogene changes of Arctic oceanography and climate can be reconstructed. The expedition was carried out by a drill platform supported by two icebreakers, which guaranteed that the platform could maintain its position without being displaced by the drifting sea ice. The 428 m of recovered sediments reach back into the Late Cretaceous and for the first time allow investigation of the evolution of Arctic climate and ocean circulation. These sediments are very difficult to date, in particular in the upper 200 m, where detrital sediments essentially barren of any fossils prevail. The sediments of the upper 150 m were dated at IFM-GEOMAR by means of the cosmogenic radionuclide ^{10}Be, which has a half-life of 1.5 million years. The dating showed that the sediments have an age of 12.3 million years at this depth and that the sedimentation rates on the order of 14.5 m/million years were similar to open ocean sites outside the Arctic Ocean (Frank et al., 2008).

Fig. 1: Drilling platform "Vidar Viking" in the foreground. Swedish icebreaker Oden Eisbrecher "Oden" and Russian icebreaker "Sovetskiy Soyuz" in the background smashed the drifting sea ice in order to keep the position of the drilling platform stable.

One of the foci of research was the timing of the establishment of the Fram Strait oceanic gateway between the North Atlantic and the Arctic Ocean, which had previously only been accessible through tectonic modeling. Above a 26 million year hiatus the ACEX sediments have an age of 18.2 million years and are characterized by organic-rich sediments that also prevailed prior to the hiatus and document that the deep Arctic Ocean was not well-ventilated but was rather an enclosed brackish basin which more resembled a large lake. At a depth of 190 m and an age of 17.3 million years there is a sharp transition from the organic-rich, black sediments to organic–poor brownish

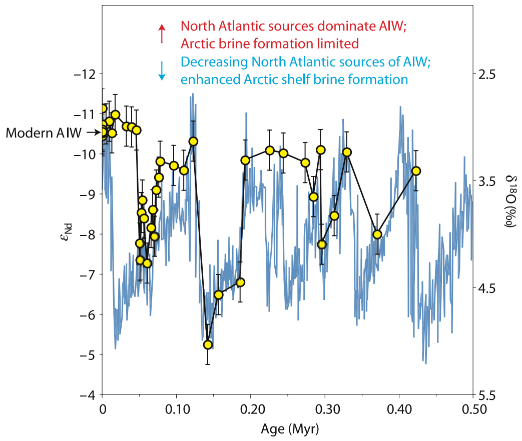

Fig. 2: Nd isotope composition of the past 400 kyr (yellow circles). The blue curve represents the oxygen isotope composition of global sea water showing the cyclic alternations between glacial and interglacial stages of the Late Quaternary.

sediments. This color change documents an increased supply of oxygen and thus the onset of deep ventilation. This ventilation could only be established with the Fram Strait open to an extent that allowed large amounts of salt-rich Atlantic waters to penetrate the Arctic Ocean and supply oxygen to intermediate and deep waters (Jakobsson et al., 2007). The early opening was confirmed by new tectonic information as well as a model constraining the minimum width of the opening strait to allow deep convection. It was also inferred that the Fram Strait fully opened to similar depths as at present of about 2,000 m by 13.7 million years.

Most of the deep Arctic Ocean today is filled with Atlantic waters exchanging through Fram Strait, which today has a sill depth of about 2,500 m. A pronounced and stable freshwater layer at the surface originating from inputs of the large Russian rivers almost completely prevents any significant deep water formation in the Arctic Ocean itself.

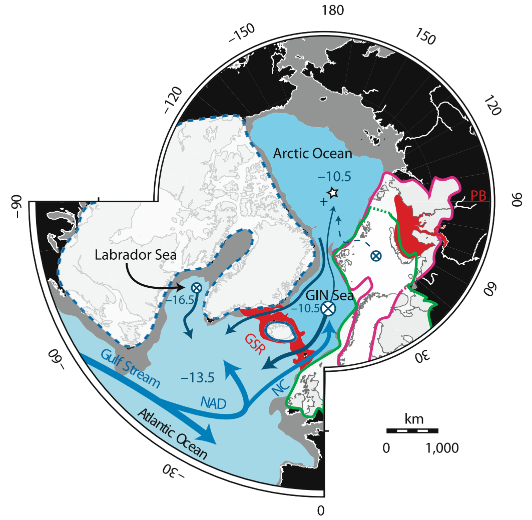

Fig. 3: Schematic Map of the present day Arctic and North Atlantic Oceans. Important currents and their corresponding Nd isotope compositions are given by arrows (blue for surface, black for deep including major areas of deep water production marked by crosses) and the distribution of the ice sheets is marked by white areas (penultimate glacial period - red outline, last glacial period - green outline). The red area marks the distribution of the weathering products of the Putorana Flood Basalts (PB). The location of the investigated sediments is given by the star.

New results obtained from the ACEX core show that this situation was an exception rather than the rule for most of the past 15 million years (Haley et al., 2008). This conclusion was drawn on the basis of the seawater isotope ratio of the element neodymium ($^{143}Nd/^{144}Nd$) that was extracted from the sediments. The Nd, which has characteristic isotope ratios in rocks as a function of their type and age, is transported to the ocean through weathering, where it provides information on the sources of water masses. Surprisingly, the results showed that the Nd isotope signature of the seawater was much higher (more radiogenic) than the present day values, with the exception of the warm periods of the past 400,000 years (Fig. 2). Such signatures indicate a pronounced influence of the weathering of basaltic rocks but on the Circum-arctic landmasses such rocks only exist in the form of the Siberian "Putorana flood basalts".

From this geologically unique setting and taking into account the evolution of the continental ice sheets of the past 140,000 years, it was then possible to reconstruct the circulation history of the deep Arctic Ocean. The signature of the basalts can only have arrived at 1,000 m water depth in the central Arctic Ocean if vast amounts of new sea ice formed near the basalt areas in the Kara Sea area (Fig. 3). During sea ice formation the salt of the sea water freezes out and is rejected, thereby forming highly saline brines, which were denser than the surrounding sea water. These brines sank and transported the dissolved Nd isotope signature of the basalts to the sea floor where the sediment cores were recovered. Further, the obtained Nd isotope variations imply that the inflow of Atlantic waters was significantly reduced during most of the past 15 million years and during the glacial periods of the past 400,000 years despite a fully opened Fram Strait. This also implies that the formation sites of North Atlantic Deep Water, which has been a very important component of global ocean circulation and of heat transfer between low and high latitudes, were most of the time not located in the Norwegian-Greenland Sea, similar to today, but further south, similar to the glacial periods of the Pleistocene.

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